

The University of Chicago

EXPERIMENTAL INVESTIGATION
OF NEGATIVE CORONA
ONSET

A DISSERTATION SUBMITTED TO THE FACULTY
OF THE DIVISION OF THE PHYSICAL SCIENCES
IN CANDIDACY FOR THE DEGREE OF DOCTOR OF
PHILOSOPHY

DEPARTMENT OF PHYSICS
SEPTEMBER, 1942

By
LOUIS ERWIN PINNEY

CHICAGO, ILLINOIS
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ABSTRACT

Using concentric cylinder electrodes, observations were made on negative corona at pressures between 1 and 10 cm of mercury. Onset potentials were observed in hydrogen and argon, and surface fields for cathodes of various radii were calculated. Definite departures from Townsend's Principle of Similarity were found. These departures may be explained in terms of photoelectric effect and photoionization from excited atoms or by the formation of space charges before the corona pulse occurs. Steady corona could be obtained in argon to a pressure as high as 10 cm of Hg. A trace of oxygen restored the pulse corona. No ionization by positive ions produced by x-rays could be observed at potentials below onset. Currents maintained by photoemission from the cathode showed rapid increase in magnitude at applied potentials about 50 volts below corona onset. The pulse frequency just above onset increased when the cathode was illuminated with very weak ultraviolet light.



INTRODUCTION

Few experimental studies of negative corona at reduced pressures, between 10 and 100 mm of mercury, have been made using concentric cylinder electrodes.^{1,2} The discharge from positively charged wires has, on the other hand, been extensively studied because of the application of this discharge to Geiger counters. Several investigations of the potential at which the corona starts^{3,4,5} have shown agreement with the empirical formula $E/p = A - B/(ap)^{1/2}$, where E is the field at the surface of the inner cylinder when the corona appears, p is the gas pressure; a is the radius of the central electrode, and A and B are constants for any particular gas. While most of these measurements have been made with air, Lee and Kurrelmeyer⁶ used several gases, including hydrogen and helium. At pressures from one atmosphere down to 4 mm of mercury they found verification for the relation just quoted.

¹L. B. Loeb, Fundamental Processes of Electrical Discharge in Gases (New York, John Wiley and Sons, 1939), p. 506.

²L. B. Loeb and J. M. Meek, The Mechanism of the Electric Spark (Stanford University, California, Stanford University Press, 1941), p. 170.

³K. K. Darrow, Electrical Phenomena in Gases (Baltimore, The Williams and Wilkins Company, 1932), p. 299.

⁴F. A. Maxfield and R. R. Benedict, Theory of Gaseous Conduction and Electronics (New York, McGraw-Hill, 1941), p. 305.

⁵W. O. Schumann, Elektrische Durchbruchfeldstärke von Gasen (Berlin, Springer, 1923).

⁶F. W. Lee and B. Kurrelmeyer, Am. Inst. El. Eng. Trans. 44, 184 (1925).

On the theoretical side we have Townsend's Principle of Similarity^{7,8,9} which requires $Ea = f(pa)$. This relation is based on general consideration of the effects on ionization due to changes in dimensions and pressure. By multiplying both sides of the empirical relation by pa we see that it is in agreement with this principle of similarity. Townsend analyzed the observations of Watson¹⁰ and those of Townsend and Edmunds,¹¹ and concluded that their observations verify this relation.

In this paper careful measurements of the minimum potentials (onset potentials) required to initiate a corona discharge between concentric cylindrical electrodes are reported for hydrogen and argon at pressures between 20 and 100 mm, using three different central electrodes. These observations show definite systematic variations from the relations mentioned in the previous paragraph. In addition, observations are reported in connection with effects produced by ultraviolet light and x-rays.

⁷Loeb, op. cit., p. 506.

⁸Darrow, op. cit., p. 305.

⁹J. S. Townsend, Electricity in Gases (Oxford, Clarendon Press, 1915), p. 367.

¹⁰E. A. Watson, The Electrician 64, 709 (1910).

¹¹J. S. Townsend and P. J. Edmunds, Phil. Mag. 27, 789 (1914).

APPARATUS

Description of apparatus.-- The corona chamber (Fig. 1) comprises a cylindrical body of 5 inch diameter brass tubing with flat end pieces containing axial openings with tubular taper fittings. These fittings receive the glass parts G which support the cathode C. A third fitting, on the top of the chamber, provides entrance for an x-ray beam directed parallel to the axis but near the cylindrical wall. A double-taper glass tube connects this fitting with the body of a small T-shaped metal x-ray tube, only the lower part of which is shown in the figure. The thin bulb-shaped window W, made integral with the surrounding glass tube, separates the vacuum space of the x-ray tube from the corona chamber. A loose brass part below the window contains slits which define the x-ray beam. A fourth tubular fitting covers a vertical slot in the side of the chamber and is closed on the outer end by a quartz window. The actual position of this fitting is about 20 degrees to one side of the path of the x-ray beam. Smaller tubulations, in the bottom of the chamber, provide connections with the gas supply and pump, and also with a mercury manometer segregated by a refrigerated trap. All seams in the brass parts are soldered. The taper ground surfaces of the glass parts, and the quartz window, are cemented to the metal with picein.

The brass guard tubes surrounding the ends of the cathode slip over the central heavy-wall members of the glass end-fittings and are held in place by tungsten leads L which provide connections to ground. The cathode rests on the tungsten lead T in

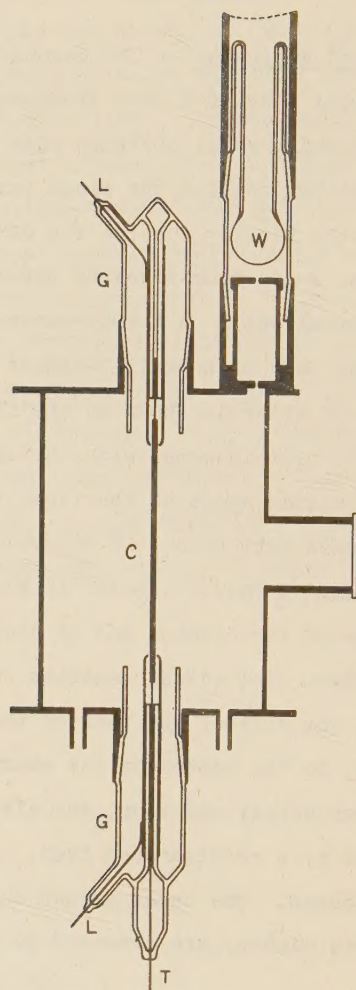


Fig. 1.--The corona chamber.
Metal parts are in black. Glass parts
are shown in outline only.

the lower glass fitting and is centered at both ends by close fit in the surrounding glass tubes.

A diagram of the electrical connections is shown in Fig. 2. Parts connected with the body of the chamber belong to the potential supply, which also includes a Raytheon voltage stabilizer, a Variac transformer, and a suitable step-up transformer with tubes for full-wave rectification. Connections from the central electrode (cathode) lead to the measuring equipment. The electrical shielding (not shown in the diagram) which encloses the condenser C_2 , electrometer E, key contacts, and lead to the cathode, is sealed at all joints with wax or tape and fitted with drying flasks containing phosphorus pentoxide.

Manipulation of apparatus.-- The current measuring equipment provided considerable flexibility as to method of use. For the very weak but comparatively steady ion-currents, charge was allowed to accumulate on the condenser C_2 during a timed interval and the resulting potential was measured by the electrometer E. Null use of this instrument was made possible by applying a compensating potential, read on the voltmeter V_2 , to the opposing set of condenser plates. The arrangement of keys and method of manipulation provided protection to the electrometer in case of unexpected electrical breakdown. If, during the charging period, any current was indicated by the meter M in the anode lead, the procedure was interrupted by grounding the condenser C_2 without connecting the electrometer.

For intermediate current ranges a more direct method was provided by connecting the cathode to ground through the resistor R_2 , with an additional resistor R_3 in series to permit application of the compensator (with polarity reversed) to the terminal P. Larger currents were measured by a sensitive galvanometer with

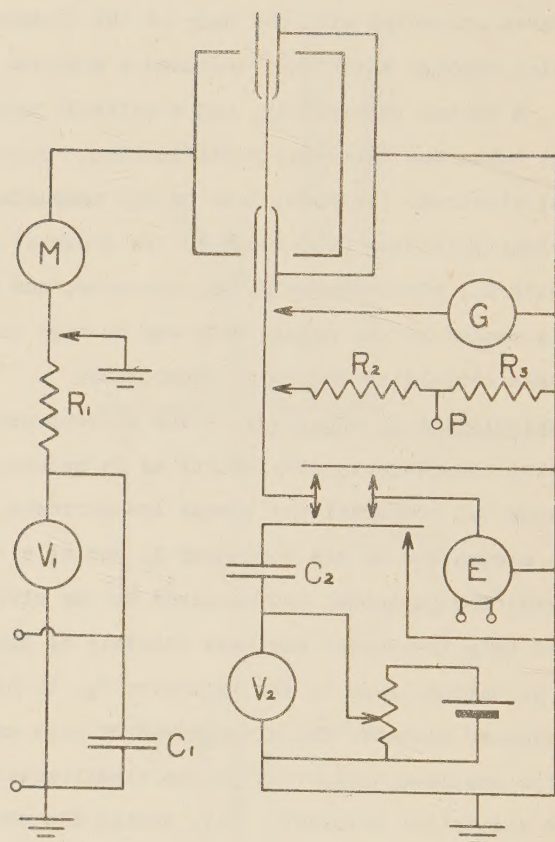


Fig. 2.--Potential supply and current measuring equipment.

adjustable shunt, and were examined for fluctuations by a cathode ray oscillograph.

All data in this report were taken with nickel cathodes. Values of surface field for the three sizes designated as A, B, and C were calculated from the formula $X = V / (r \log \frac{R}{r})$ where R is 6.18 cm, the radius of the outer cylinder, and r is 0.102 cm for A, 0.064 cm for B, and 0.040 cm for C.

The design of the cathode assembly was such as to weaken the field at the ends of the cathode, near the guard tubes, and, judging by behavior of the corona spots, to provide nearly constant field over a considerable length in the middle. This conclusion is based upon the fact that the corona, while avoiding the end regions, wandered rather freely up and down the middle portion of the cathode.

Illumination for liberating photoelectrons from the cathode was provided by a D C quartz mercury arc. High intensity was obtained by the use of a quartz lens. Removal of the lens decreased the intensity by a factor calculated as 0.06. Much lower intensity was obtained by placing a screen containing a small hole in front of the arc tube.

The x-ray tube was operated by a 6000 volt constant-potential source, which restricted the radiation to long wavelengths with the desired high absorption coefficient and short range of secondary radiations. The position of the x-ray beam in the chamber was such that the negative ions were removed by a field too weak to impart ionizing velocities.

NEGATIVE CORONA UNDER NORMAL ONSET CONDITIONS

General characteristics of negative corona discharge.--

The gas pressures and the radii of the inner cylinders (cathodes) were such as to inhibit sparking and favor glow discharge. This discharge, or corona, was of either steady or pulse type. The pulse type of negative corona discharge consists of discrete electrical pulses beginning with random time spacing at a sharply defined onset potential. With increase in potential above the onset the pulses become more and more numerous and at the same time approach a state of definite periodicity. These pulses, first described by Trichel,¹² are usually referred to as "Trichel pulses". Beyond this state, the frequency of the resulting oscillations increases with the potential; and, throughout the entire range of these pulses or oscillations, the various stages are completely reversible with respect to voltage.

Except near the onset, where the mean value of the current is extremely small, the pulse corona can be observed visually as a glow on the cathode. The glow is invariably concentrated in small spots,¹³ usually only one, but sometimes two and occasionally three. The single spot corona frequently wanders up and down the cathode.

The pulse corona does not exhibit the negative resistance characteristic found in most arc and glow discharges. This fact

¹²G. W. Trichel, Phys. Rev. 54, 1080 (1938).

¹³In case of multiple spot corona, the discharge is believed to alternate between the spots. This conclusion is based on oscillographic examination of the corona current.

was established by varying the protective resistance R_1 (Fig. 2) through wide limits without appreciable effect.

The steady type of negative corona discharge exhibits a very pronounced negative resistance characteristic and is free from any inherent pulsation or periodicity.¹⁴ Hence, it appears that this type of corona, insofar as cathode effects are concerned, has much in common with the usual forms of glow discharge.

Corona types in different gases.---¹⁵ The pulse type corona was observed in hydrogen and in air, and the steady type in nitrogen. In argon¹⁶ either type could be obtained, with the pulse type favored by higher pressures and the presence of small amounts of other gases, notably oxygen.

Argon was used throughout the preliminary work with the result that only the pulse corona was observed, but later, when precautions were taken to secure greater purity of the gas, the steady type of onset was observed at the lower pressures. With further improvement in purity, which involved ionic bombardment of the cathode at low pressure (sputtering conditions) and repeated flushing of the chamber, it became possible to eliminate the pulse corona at pressures as high as 100 mm of mercury. On the other hand, the addition of as little as 0.1 per cent of oxygen was sufficient to restore this type of discharge at pressures as low as 10 mm. In a recent abstract Weissler¹⁷ reports

¹⁴At a certain voltage adjustment oscillations, of a frequency dependent upon anode to ground capacitance, were observed.

¹⁵The different gases were used solely to study the factors influencing corona onset, and the dependence of onset potentials on the pressure and the curvature of the cathode. No claim is made that the potentials observed are those that would be found as characteristic of absolutely pure gases.

¹⁶Tank argon containing one per cent of unspecified impurity.

¹⁷G. L. Weissler, Phys. Rev. 61, 205 (1942).

that hydrogen, nitrogen, and argon, when sufficiently pure, do not yield Trichel pulses, presumably because these gases do not form negative ions. The author's observations agree with Weissler's findings as to the effect of oxygen as an impurity.

Onset potentials in hydrogen and argon.-- Onset potentials for the pulse corona in hydrogen were measured at pressures between 10 and 90 mm of mercury. In order to show the relation to the theoretical formula, the surface field E (volts per cm) at onset was computed. It was found, on plotting, that the data do not agree with the formula $E/p = A + B/(pa)^{\frac{1}{2}}$ where A and B are to have one set of values for the three cathodes. Inasmuch as this formula is a special case of Townsend's Principle of Similarity, $Ea = f(pa)$, the data were plotted (Fig. 3) with pa as abscissas and Ea as ordinates. It is evident that the points fall on three distinct curves A, B, and C, which refer to the three cathodes $a_1 = 0.102$ cm, $a_2 = 0.064$ cm, and $a_3 = 0.040$ cm.

With argon slightly contaminated with oxygen, negative pulse corona was also observed. The potentials were somewhat less reproducible than for hydrogen. In this gas a further increase in potential following the initial onset frequently caused a sudden transition to the steady corona.

With purer argon, as explained above, steady corona at initial onset was obtained. The onset potentials were observed and the surface fields at the cathodes were calculated. Here, as in the case of the pulse corona in hydrogen, the observations fitted three curves of the type $E/p = A + B/(pa)^{\frac{1}{2}}$. The values of Ea are plotted against pa in Fig. 4. If the principle of similarity held, we would expect the values to be connected by the relation $Ea = f(pa)$, but, as in the case of hydrogen, the data fall on three distinct curves.

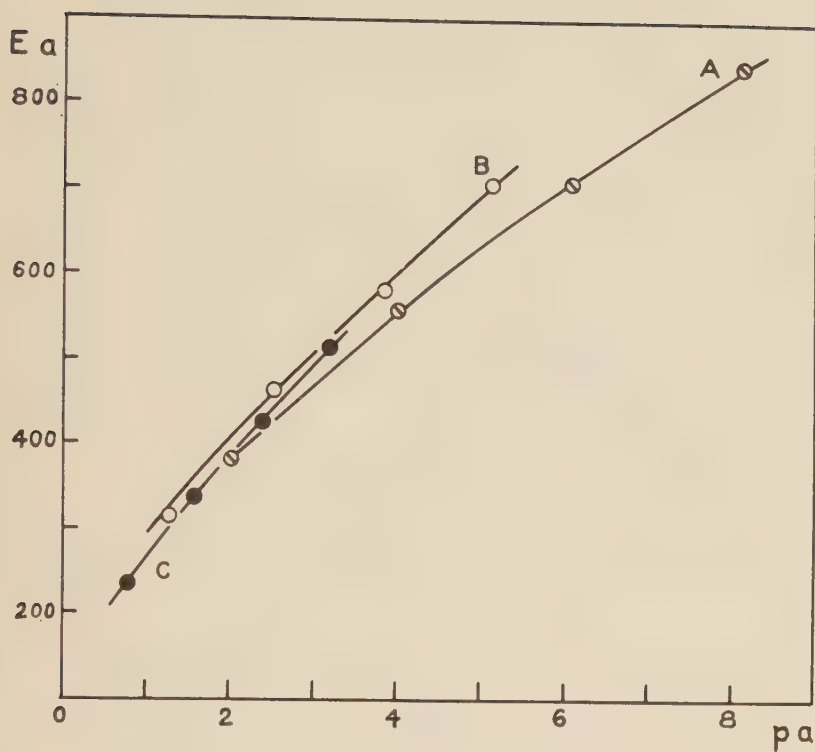


Fig. 3.-- $Ea = f(pa)$ for hydrogen. E in volts/cm, a in mm of Hg, and p in cm.

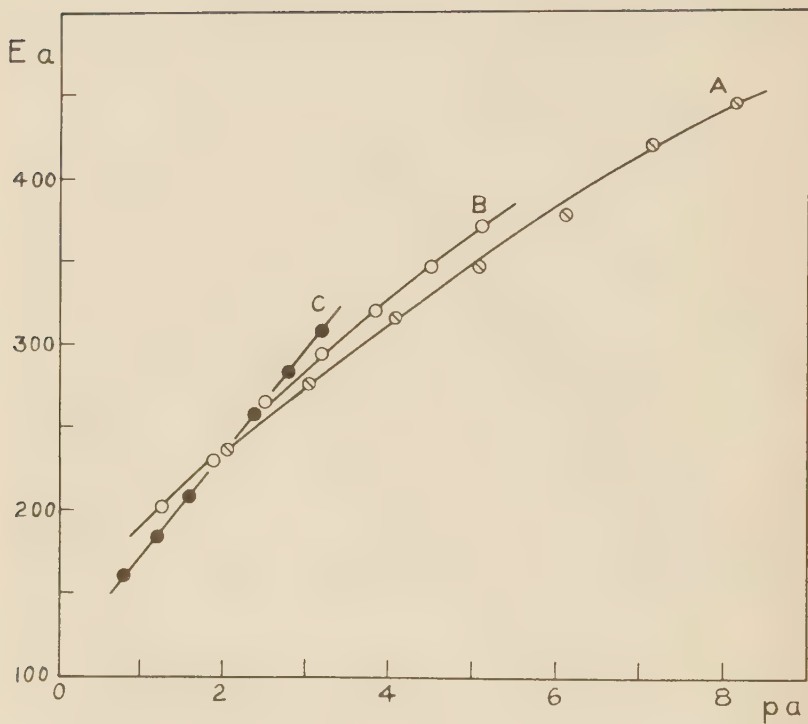


Fig. 4.-- $E_a = f(pa)$ for argon. E in volts/cm, a in mm of Hg, and p in cm.

The formula

$$Ea = Ae^{Bp/E} \quad (1)$$

for the surface field E in terms of cathode radius a and pressure p was deduced by Schumann.¹⁸ The radius of the anode is so large (6.18 cm) that it does not enter into the formula. The observations of the author are in excellent agreement with formulae of this kind, but new constants A and B must be chosen for each radius of the cathode. This fact again shows departure from the principle of similarity. Seeliger¹⁹ gives a derivation of formula (1) and states that the observations of Lee and Kurrelmeyer,²⁰ taken with only one diameter of central electrode, agree with this relation. He also gives the constants required to fit their observations.

The present observations agree with the equation

$$\log_{10} Ea = C + Dp/E \quad (2)$$

where the constants C and D for the three cathodes of different radius have the values given in Table 1.

TABLE 1

CONSTANTS IN FORMULA (2) FOR SURFACE FIELD E IN VOLTS PER CM AT NEGATIVE CORONA ONSET IN HYDROGEN AND ARGON WITH THREE CATHODES
(p in mm)

Cathode Radius (cm)	Argon		Hydrogen	
	C	$D \times 10^4$	C	$D \times 10^4$
$a_1 = 0.102$	2.14	27	2.12	83
$a_2 = 0.064$	2.10	34	2.05	108
$a_3 = 0.040$	1.88	58	1.95	120

¹⁸Schumann, op. cit., p. 174.

¹⁹R. Seeliger, Physik der Gasentladungen, (Leipzig, J. A. Barth, 1927), p. 214.

²⁰Lee and Kurrelmeyer, op. cit., p. 184.

There is a decrease in C and an increase in D with decreasing radius of the central cathode. Any one of the other relations deduced by Schumann would also necessarily prove inadequate for all three radii, since they also imply agreement with the principle of similarity.

Nitrogen also gave steady corona at onset, but satisfactory curves were not obtained. In this gas, and to less extent in argon, there was a well defined but irregular time lag in the steady corona onset. As a consequence, values approaching a minimum were obtained only by the rather tedious procedure of increasing the voltage by small steps and, after each step, waiting to see whether onset would occur.

Breakdown of principle of similarity.-- The observations of Watson²¹ and Townsend and Edmunds,²² which appeared to confirm the principle of similarity, were not very precise. The individual values of E_a varied as much as five per cent from the mean curve given by Townsend and Edmunds. The radii of their inner cylinders ranged from 2.38 mm to 0.03 mm, and the range of p_a was from 0.05 to 20. A study of the tables²³ in their paper, however, does show a general tendency for E_a to be greater for the smaller inner cylinders at the same value of p_a . This feature, of which they made no mention, is in agreement with the present paper. Furthermore, Townsend and Edmunds placed all emphasis on the approximate agreement with the principle of similarity which was first derived from theoretical considerations by Townsend²⁴ in the preceding year, and which had then been considered as con-

²¹Watson, op. cit., p. 709.

²²Townsend and Edmunds, op. cit., p. 789.

²³Ibid.

²⁴J. S. Townsend, The Electrician 71, 348 (1913).

firmed by the measurements of Watson.²⁵ Huxley²⁶ gives curves for the corona potential in nitrogen. His data also show a departure from Townsend's law for negative corona, but no comment is made. A discrepancy is also shown in observations of Boulind²⁷ in oxygen at low pressure, but is ascribed to the region of ionization extending to the outer cylinder.

The departures from the principle of similarity shown in Figs. 3 and 4 consist of a more rapid increase of E_a with increasing pressure (pa) for the small than for the large cathodes. The most immediate explanation is to attribute part of the breakdown process to photoionization of impurities or photoelectric emission from the cathode due to radiation from excited atoms which are produced by electron impact. If the pressure is high, the energy of excitation is transferred to kinetic energy of the colliding atoms or molecules, the breakdown process is thus hindered, and consequently a higher field is required than would otherwise be necessary. Since the rate of quenching²⁸ depends directly on the pressure, we have here a factor that produces a departure from the principle of similarity.²⁹

Photoelectric emission has been suggested as an important element in the breakdown,³⁰ and photoionization has been discussed in connection with the corona from negative points by Loeb, Kip, Hudson and Bennett.³¹

²⁵Watson, op. cit., p. 709.

²⁶L. G. H. Huxley, Phil. Mag. 10, 185 (1930).

²⁷H. F. Boulind, Phil. Mag. 18, 909 (1934).

²⁸A. E. Ruark and H. C. Urey, Atoms, Molecules and Quanta (New York, McGraw-Hill, 1930), p. 495.

²⁹Darrow, op. cit., p. 299.

³⁰Loeb, op. cit., p. 383.

³¹L. B. Loeb, A. F. Kip, G. G. Hudson, and W. H. Bennett, Phys. Rev. 60, 721 (1941).

It has been pointed out by Darrow³² that the principle of similarity is likely to fail if space charges are important. These charges begin to influence the potential distribution just before the sparking potential is reached, but change the expected breakdown potential very little.³³ It is possible that even at the lowest potentials just sufficient for the negative corona, there is already an increased field established near the cathode and a cathode dark space which serves the purpose of providing electrons for the discharge. On this view we might consider the corona discharge as beginning at the outer edge of the cathode dark space. If the thickness of the dark space, which in hydrogen is given in mm by $9.3/p$, is added to radius a , we find an effective radius r . The field at r is calculated from the potential difference diminished in the case of hydrogen by 215 volts, the cathode fall of potential. It is found that with these effective radii and fields the principle of similarity does hold.

³²Darrow, op. cit., p. 308.

³³W. O. Schumann, Zeitsch. f. Tech. Phys. 11, 58, 131, 194 (1930).

NEGATIVE CORONA ONSET IN THE PRESENCE
OF AUXILIARY IONIZING AGENCIES

Effects of x-rays and ultraviolet light on ionization currents.-- It was observed by Whitehead³⁴ that the onset potentials for positive and negative corona in air at atmospheric pressure are independent of ionization by x-rays.

In the present experiments a possible current increase at low pressure due to the impact of positive ions on the cathode was looked for. The chamber was filled with argon to a pressure of 55 mm and the ionization current produced by the x-rays was observed at various potentials applied to the cathode of 0.64 mm radius. It was found that the saturation current did not increase as the potential was increased to values at which pulses began. Since a rise of one per cent or more would have been detected, it may be concluded that there was no appreciable ionization by positive ions or increase in current due to impact of positives on the cathode.

The field at the surface for corona onset in argon is $E \approx 4685$ volts per cm or $E/p = 85$. Direct observations of β do not extend to such low fields, but extrapolation³⁵ would indicate $\beta = 0.15$ for the maximum value at the surface of the cathode. Since the field decreases rapidly with distance from the cathode, it is not surprising that no ionization by the positive ions could be observed.

³⁴I. B. Whitehead, Trans. Am. Inst. El. Eng. 30, 96 (1911).

³⁵A. V. Engel, and M. Steenbeck, Elektrische Entladungen (Berlin, Springer, 1932), I, p. 107.

When ultraviolet light was allowed to fall on the cathode, the current showed steadily increasing amplification from one-tenth the corona onset potential to a value near onset. A much more rapid increase in the current with voltage began about 50 volts below the pulse onset. This effect for argon is shown in Fig. 5, and for hydrogen with fainter illumination in Fig. 6. This rapid upturn in the curves about 50 volts below onset was observed in the two gases with pressures ranging from 2 to 7 cms of mercury. It could be shown that the large currents just below onset were not due to superimposed corona pulses mistakenly attributed to steady ionization. These corona pulses, under the pressure conditions of Fig. 6, using potentials just above onset, had an average value of about 5.8×10^{-9} coulombs. This amount of charge was much too large to escape notice if it had been superimposed on or included in the photoexcited currents shown in Fig. 5. This conclusion is verified by the fact that extinguishing the illumination with applied potentials between upturn and onset completely shut off the current. The rapid upturn in photoexcited current might be attributed to an increase in the ionization efficiency of the electrons at this applied voltage. However, since the field varies inversely as the distance from the center, there is present at any one applied voltage a field that varies continuously from a maximum at the cathode to a minimum at the outer electrode, and no sudden change in the total ionization would be expected from a slight change of one per cent in the total applied potential. It is possible that the rapid upturn is associated with the formation of a space charge and the establishment of a new field distribution near the cathode which gives rise to increased ionization in the neighborhood of the electrode.³⁶

³⁶Loeb, op. cit., p. 506.

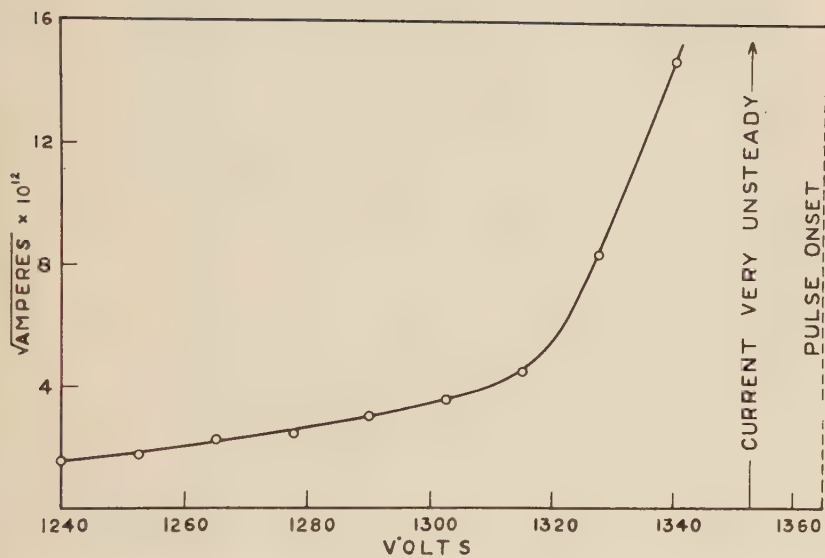


Fig. 5.--Photo excited current in argon at potentials near corona onset.

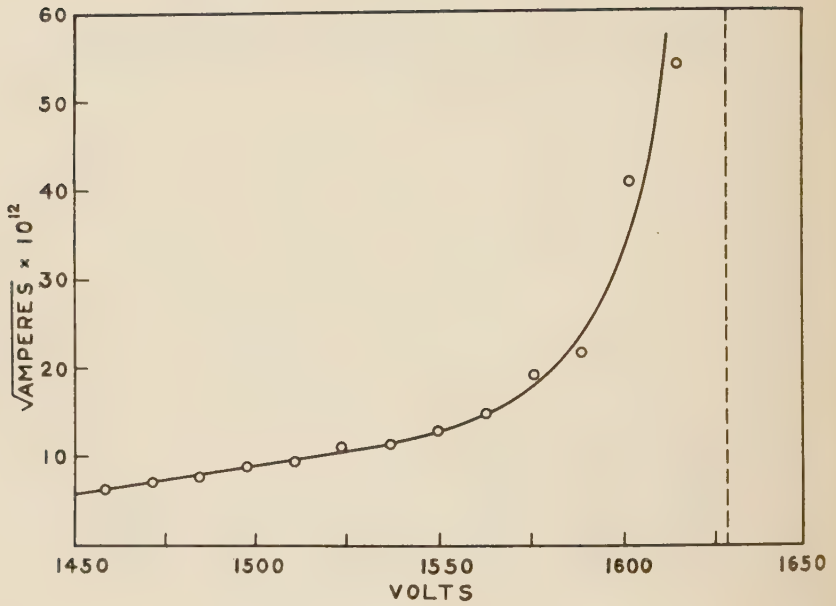


Fig. 6.--Photo excited current in hydrogen at potentials near corona onset. B cathode. $p = 26$ mm. Here the illumination was decreased to 0.06 of the intensity used in Fig. 5.

Effect of x-rays and ultraviolet light on pulse frequency.

In argon with potentials just above onset it was possible to count the pulses and also to measure the charge in each pulse. The pulse frequency increased with increasing potential and also with ultraviolet illumination on the cathode. It was possible to observe an increase in the pulse frequency with very weak illumination. By placing a screen with a small hole in front of the arc tube, the intensity on the cathode could be reduced to 2×10^{-5} times that used in the observations of Fig. 5. By counting pulses with the arc on and off in alternate one-minute intervals, it was found that five times as many pulses were obtained with the arc on.

With x-rays there was also an increase in frequency comparable in magnitude to that obtained with the weak ultraviolet illumination. It is likely that this effect was due to scattered and fluorescent radiation rather than to positive ion impact, since the effect with ultraviolet illumination suggests that the pulses are dependent on emission of electrons from the cathode surface.

The author takes pleasure in acknowledging the assistance of Professor A. J. Dempster in the preparation of the foregoing paper. Thanks are also due the Physics Department of Iowa State College, which supplied much of the equipment originally set up at Ames and later moved to Chicago.

